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Gigahertz pulse source by compression of mode-locked VECSEL pulses coherently broadened in the normal dispersion regime

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Abstract: We report the coherent spectral broadening of the output of a mode-locked VECSEL emitting 455 fs pulses at 1007 nm in the normal-dispersion regime. Subsequent compression of the fiber outputs using a transmission grating compressor produced 1.56 GHz trains of 150 fs pulses at 270 mW average power or 220 fs pulses at 520 mW average power. The system approaches the performance needed for a pump for coherent supercontinuum generation.

OCIS codes: (320.7090) Ultrafast lasers; (320.5520) Pulse compression; (140.5960) Semiconductor lasers

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1. Introduction

Recent demonstrations of femtosecond mode-locked VECSELs with Watt-level output powers [1–3] have fuelled interest in their possible use as pump sources for gigahertz-mode-spacing frequency combs. In addition, demonstrations of repetition-frequency-tunable femtosecond VECSELs [4] and of femtosecond MIXSELs [5], close relatives of VECSELs with a large degree of repetition frequency flexibility, have demonstrated that this family of lasers has great scope as pumps not only for high frequency comb generation, but also for generation of frequency combs with variable comb spacing. Femtosecond VECSELs have also been demonstrated in the 2 μm spectral region [6], where frequency combs have attracted interest as tools for a range of spectroscopic applications. To date, however, while VECSELs have been used for supercontinuum generation both directly [2] and in fiber-amplified configurations [7], the majority of the resulting supercontinuua have been incoherent, primarily as a result of the pulse durations of the VECSEL pumps, which are typically in the few-hundred femtosecond range rather that the sub-200-fs pulses which would be suitable for coherent supercontinuum generation when soliton effects are present [8].

At sub-Watt-level output powers, mode-locked VECSEL pulse durations have been reduced from 22 ps in the first demonstration [9] to durations below 200 fs [10, 11]. However, similar pulse durations at average powers greater than 1 W have not been achieved. It is not clear that achieving sub-200-fs pulse, multi-Watt-level VECSELs will be possible simply by incremental steps towards higher performance. Microscopic modelling of mode-locked VECSELs has shown that kinetic holeburning occurs as the pulse duration approaches the carrier-carrier scattering times in the semiconductor [12]. This is consistent with the observed behavior of low power VECSELs, where sub-200-fs pulses have only been observed as trains of pulses with dynamics governed by kinetic holeburning [10], or as single pulses with very low energies [11]. Further proof of the effects of kinetic holeburning has come from dual wavelength CW VECSELs [13], and the theoretical modelling of their behavior [14].

Given that kinetic holeburning presents an obstacle to constructing VECSELs with performance levels suitable for direct generation of coherent supercontinuua, it is necessary to explore other routes to generating high power trains of sub-200-fs pulses at GHz repetition rates. This paper describes the experimental demonstration of a system based on the spectral broadening and compression of VECSEL pulses. Coherent spectral broadening of a 455 fs, 1.4 W VECSEL is performed in the normal dispersion regime [8, 15] in two different pieces of photonic crystal fiber. Self-phase modulation is the dominant broadening mechanism in the normal dispersion regime, and the lack of soliton effects yields low-noise pulses with parabolic phase that is consistent from shot-to-shot. Pulse compression of the outputs of the two fibers in a transmission grating compressor resulted in 1.56 GHz trains of either 150 fs pulses at 270 mW average power or 220 fs pulses at 520 mW average power.

2. VECSEL pump laser

The VECSEL gain sample used in this work was an antiresonant design, grown by NAsP III-V GmbH, containing 10 InGaAs quantum wells in an 11λ/2 long microcavity designed for operation at 1015 nm. The sample was flip-chip bonded to a 0.3 mm thick diamond heatspreader which was mounted on a water-cooled copper block. The laser cavity was formed between a 1.45% output coupler with 100 mm radius of curvature and a surface recombination SESAM, with the gain sample as a folding mirror. The gain sample and

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SESAM were identical to those used in [2]. The gain sample was pumped with up to 25 W in a 300 μm diameter spot using a fiber-coupled 808 nm diode system, and the ratio of mode areas on the gain sample and SESAM was estimated to be 2:1. The SESAM heatsink was held at a temperature of 16 °C by a thermoelectric cooler and the gain sample heatsink temperature at 17 °C. A diagram of the laser is shown in Fig. 1.

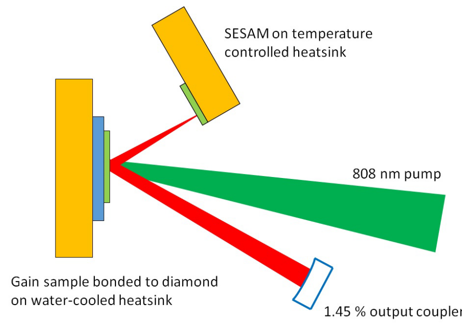

Fig. 1. Schematic of the mode-locked VECSEL. The ratio of the mode areas on the gain sample and the SESAM was 2:1 and total cavity length of 96 mm resulted in a repetition rate of 1.56 GHz.

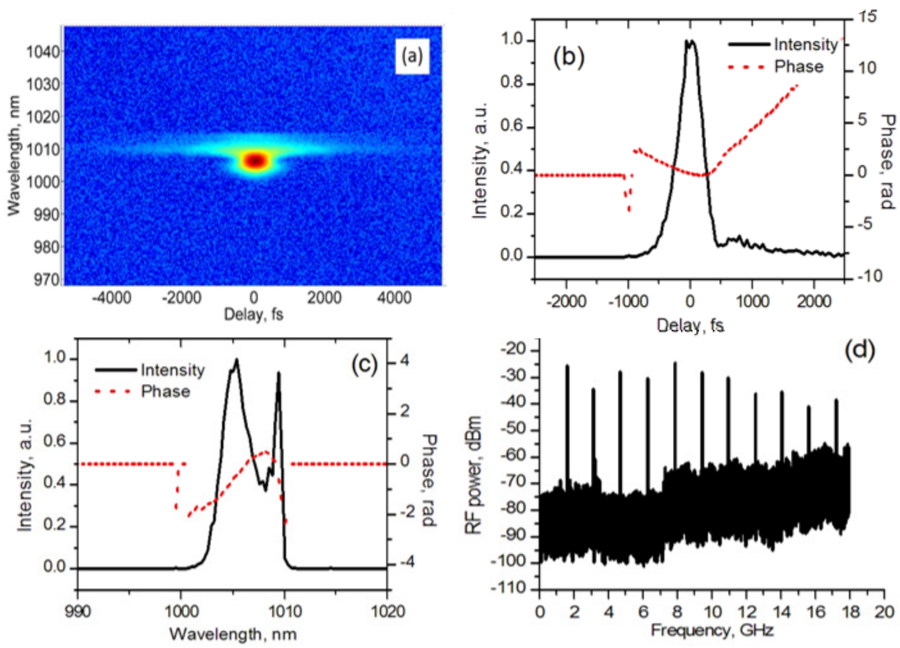

Fig. 2. FROG spectrogram (a) of the laser output, extracted temporal (b) and spectral (c) characteristics indicating a FWHM pulse duration of 455 fs and a FWHM bandwidth of 3.4 nm centered at 1007 nm. (d) RF spectrum of the laser output demonstrating stable mode-locking with a fundamental repetition rate of 1.56 GHz.

The laser output, at an average power of 1.4 W and a repetition rate of 1.56 GHz, was characterized using a 26.5 GHZ bandwidth RF spectrum analyzer and a MesaPhotonics FROGscan FROG system. Shown in Fig. 2 are the measured FROG spectrogram of the laser output, the extracted spectral and temporal characteristics, and the RF spectrum. The extracted FWHM pulse duration and spectral bandwidth were 455 fs and 3.4 nm centered at 1007 nm, corresponding to a time-bandwidth product of 0.46, and the RF spectrum is indicative of stable modelocking.

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3. Spectral broadening and pulse compression

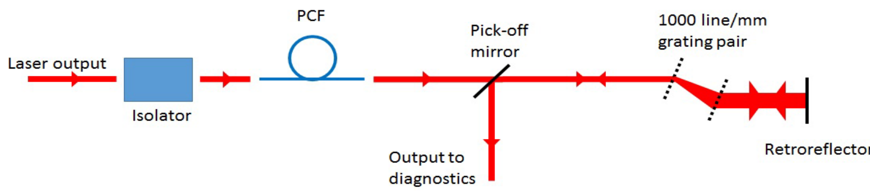

Fig. 3. Schematic of the spectral broadening and pulse compression set-up. Pulses output by the mode-locked VECSEL were broadened in one of two pieces of PCF. The compressor was based around two 1000 line/mm transmission gratings and was optimized by varying the spacing between the gratings. The compressor throughput was 80%.

The VECSEL output was launched through an optical isolator into one of two different pieces of photonic crystal fiber and then into a pulse compressor based on a pair of 1000 line/mm transmission gratings optimized for use at 1040 nm. A schematic of the system for spectral broadening and pulse compression is shown in Fig. 3. The two fibers used were a 4 m length of all-normal-dispersion fiber produced at the University of Bath (UoB fiber), and a 1 m length of SC-5.0-1040 fiber from NKT Photonics. The VECSEL wavelength was in the normal dispersion regime for both fibers, which have a dispersion minimum at 1064 nm and a zero dispersion point at 1040 nm respectively. Dispersion curves of the two fibers can be found in references [16] for the UoB fiber and [17] for the NKT fiber.

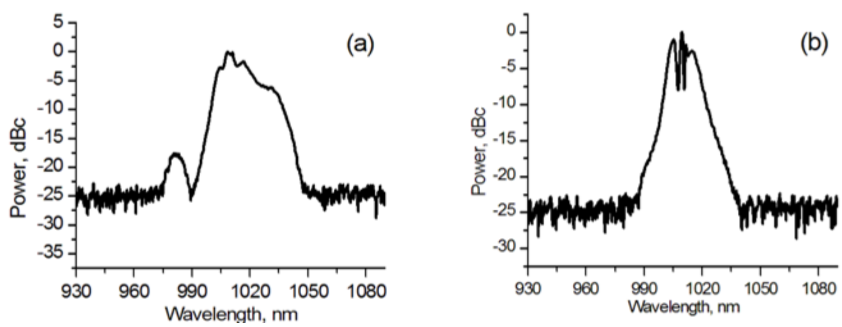

Fig. 4. Spectra of the output of the UoB fiber (a) and the NKT fiber (b) showing broadening to 20 dB bandwidths of 51 nm and 39 nm respectively.

A transmission of 45% was achieved in the case of the UoB fiber, corresponding to an output power of 650 mW, but thermal issues with the fiber coupling limited the power output from the NKT fiber to 350 mW. In both cases the launch end of the PCF was flat cleaved and no additional thermal management, such as collapsing the fiber ends or active water cooling, was used. Moderate spectral broadening was achieved in both cases, to 20 dB bandwidths of 51 nm and 39 nm respectively. Spectra of the outputs of the two fibers are shown in Fig. 4.

The output from the UoB fiber had sufficient average power for FROG measurements to examine the phase structure and to assess its suitability for compression. Measured and retrieved FROG spectrograms and the extracted temporal and spectral characteristics are shown in Fig. 5. The extracted phase in both time and frequency domains is fit well by parabolic equations. The GDD required to compensate for the linear component of the phase was calculated to be $-37200\ fs^2$ from the fit to Fig. 5(c).

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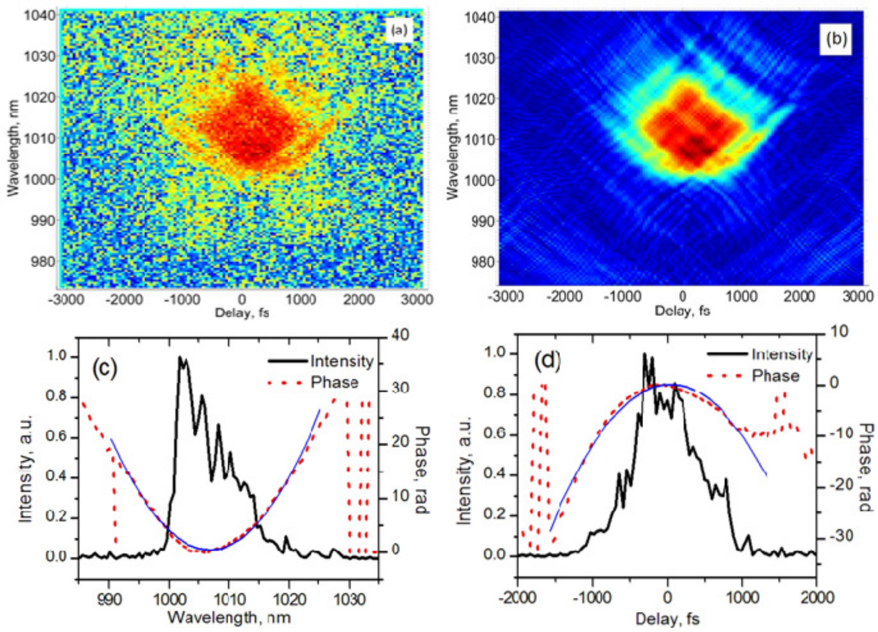

Fig. 5. Measured (a) and retrieved (b) FROG spectrograms, and extracted spectral (c) and temporal (d) characteristics of the 650 mW output from the University of Bath fiber. Blue curves are parabolic fits to the phase profiles in both spectral and temporal domains.

Compression of the outputs of both fibers was performed using a grating compressor with a throughput of 80%, based around two 1000 line/mm transmission gratings. Optimal dispersion compensation was achieved separately for the two different fibers by varying the spacing between the gratings in the range 2-10 mm. FWHM pulse durations of 150 fs at 270 mW average power or 220 fs at 520 mW average power could be achieved by compression of the NKT and UoB fiber outputs respectively. Figure 6 shows the measured spectrograms along with the extracted temporal and spectral characteristics of the compressed outputs from both fibers.

From Fig. 6(e) and 6(f) it is clear that, while the compression has given close-to-linear phase across the main body of the pulse, uncompensated higher-order dispersion has resulted in a significant proportion of the pulse energy remaining in side peaks. The main body of the pulse contains 79% of the energy in the case of the UoB fiber and 75% in the case of the NKT fiber. It is likely that in both fibers the pulse duration and the energy in the side peaks could be minimized by optimizing the length of fiber used. As such, neither system can yet be considered optimal, with the performance of the NKT fiber based system being limited by poor coupling resulting from thermal issues, and both systems suffering from incomplete pulse compression. Techniques including water cooling, angle cleaving and fiber-end-collapsing exist for making supercontinuum-generating PCFs more robust towards both high average powers and peak powers [18], and soliton compression in hollow-core PCF has been demonstrated as a means to achieving transform-limited pulse compression while rejecting higher order dispersion [16]. Improvements in these areas, and of the VECSEL pump, would be expected to yield further advances in performance.

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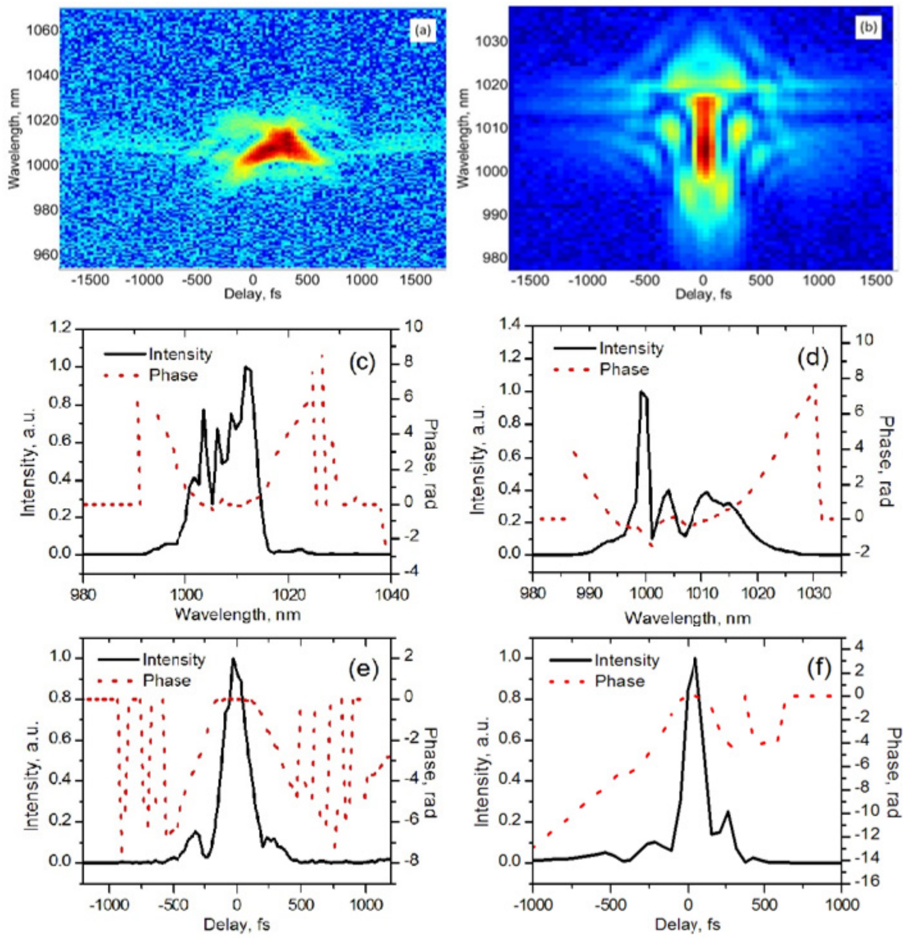

Fig. 6. FROG spectrogram, and extracted spectral and temporal characteristics of the compressed output of the UoB fiber (a), (c) and (e), and the NKT fiber (b), (d) and (f). Compression of the output from the Bath fiber yielded 220 fs pulses at 520 mW average power, compared with 150 fs at 270 mW from the NKT fiber.

4. Conclusions

We have demonstrated a 1.56 GHz repetition rate pulse source based on coherent spectral broadening and compression of a 1007nm, 1.4 W, 455-fs-pulse mode-locked VECSEL. Spectral broadening was performed in the normal dispersion regime of two different photonic crystal fibers: an all-normal-dispersion fiber with a dispersion minimum at 1064nm and a highly nonlinear fiber with a zero dispersion wavelength of 1040 nm. Compression of the outputs from the fibers resulted in trains of either 150 fs pulses at 270 mW average power or 220 fs pulses at 520 mW average power. This system presents an attractive solution as a high repetition rate pump source for coherent supercontinuum generation in the absence of VECSELs that are capable of direct pumping.

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